2(a)(i)	p = pressure (of gas), V = volume (of gas) **and** k = Boltzmann constant	**B1**
	N = number of molecules (in the gas)	**B1**
	T = thermodynamic temperature (of gas)	**B1**

2(a)(ii)	(pV =) $NkT = \frac{1}{3}Nm\langle c^2\rangle$	**M1**
	$E_K = \frac{1}{2}m\langle c^2\rangle = \frac{1}{2} \times 3kT = (3/2)kT$	**A1**

2(b)	(same temperature so) $(\frac{1}{2})m\langle c^2\rangle$ must be same for both gases	**C1**
	ratio = $\sqrt{(m_O / m_H)}$ $= \sqrt{(32/2)}$ $= 4.0$	**A1**

Question 2

(a) (i) A common error was giving the meaning of T as 'thermal dynamic' temperature. Less common errors were giving the meaning of N as the number of moles and the value of k instead of its meaning.

(ii) A significant number of candidates were careless with regard to the symbols used for mean-square speed, writing $\langle c \rangle^2$ instead of $\langle c^2 \rangle$ or $\overline{c}^2$ instead of $\overline{c^2}$. An incorrect final answer was often $E_K = \frac{3}{2}NkT$, having not cancelled N following the use of the correct starting equation. Some candidates gave two correct starting equations ($pV = NkT$ and $pV = \frac{1}{3}Nm\langle c^2 \rangle$) but did not clearly show in their derivations how these were combined.

(b) Most candidates gained at least partial credit. Common incorrect final answers were 1/4 and 16, both of which implied that the average kinetic energies of a particle in both gases were the same.

3(a)	total kinetic energy associated with random motion of molecules	**B1**
	potential energy (of molecules) is zero	**B1**

3(b)(i)	$pV = NkT$ **and** $U = (3/2)NkT$	**C1**
	$U = (3/2)pV$ $= (3/2) \times 2.0 \times 10^5 \times 0.016$ $= 4800$ J	**A1**

3(b)(ii)	temperature = 800 K	**A1**

3(b)(iii)	volume = 0.032 m^3	**A1**

3(b)(iv)	straight vertical line labelled X between A and (0.016, 4.0)	**B1**
	curve from B with continuously decreasing negative gradient, labelled Y	**B1**
	line labelled Y between (0.016, 4.0) and (0.032, 2.0)	**B1**

Question 3

(a) Some candidates did not mention random motion and/or 'total' when referring to kinetic energy. The fact that the molecular potential energy is zero in an ideal gas was well known. Some candidates did not refer to molecules or particles at all in their answers.

(b) (i) The equation $\frac{3}{2}kT$ was commonly assumed to be the correct equation to use, as the candidate had just derived it in **Question 2**. Many candidates calculated E_K for only one molecule, omitting to calculate and use N.

(ii) Most candidates gave the correct answer.

(iii) Most candidates gave the correct answer. A minority made a power-of-ten error.

(iv) A significant proportion of candidates incorrectly drew a straight line from B to C for line Y. Most candidates placed B and C in the correct positions and drew the correct line for X.

2(a)	(gravitational) force is (directly) proportional to product of masses	**B1**
	force (between point masses) is inversely proportional to the square of their separation	**B1**

2(b)	*Any two points from*: • molecules are in <u>continuous</u> random motion • molecules have negligible volume compared with volume of gas • collisions (involving molecules) are (perfectly) elastic • collisions (of molecules) are instantaneous	**B2**

2(c)(i)	$pV = nRT$	**C1**
	$p = (0.0160 \times 8.31 \times 282) / (1.87 \times 10^{-4})$ $= 2.01 \times 10^{5}$ Pa	**A1**

2(c)(ii)	number of molecules $= 0.0160 \times 6.02 \times 10^{23}$	**C1**
	separation $= \sqrt[3]{[(1.87 \times 10^{-4}) / (0.0160 \times 6.02 \times 10^{23})]}$ $= 2.7 \times 10^{-9}$ m (*allow any answer that is 3 × 10⁻⁹ m to one significant figure*)	**A1**

2(d)(i)	$F = 6.67 \times 10^{-11} \times (3.34 \times 10^{-27})^2 / (2.7 \times 10^{-9})^2$	**C1**
	$= 1.0 \times 10^{-46}$ N	**A1**

2(d)(ii)	numerical comparison between 10^{-46} N (F) and 10^{-26} N (the weight of molecule) leading to a conclusion that the assumption is supported	**B1**

Question 2

(a) This question was generally well answered, with most candidates able to give a correct statement of Newton's law of gravitation.

(b) Whilst candidates generally had a reasonable understanding of what the assumptions of the kinetic theory are, many did not articulate clearly enough that they were discussing the molecules of the gas rather than the gas itself. For example, responses such as 'gases have negligible volume' and 'gases undergo elastic collisions' were common incorrect answers. There was no credit available to candidates for repeating the assumption that was stated in the question.

(c) (i) Most candidates knew the correct starting equation and were able to use it. Some candidates did not notice that the data provided in the question was given to three significant figures and that therefore three significant figures should be given in the answer.

(ii) Many candidates realised that the starting point for this question was to determine the number of molecules in the sample. Many candidates then stopped after determining the effective volume occupied per molecule, without converting the volume into an effective distance of separation. In carrying out this last step, candidates could treat the effective space occupied by each molecule as a cube or a sphere, leading to an effective mean separation of the order of 10^{-9} m.

Many answers were seen that were many orders of magnitude away from being plausible, and this was a good example of a question in which taking time to consider whether the answer makes sense can lead to detection of an error in the working. For example, a candidate that stops at the volume and arrives at an answer of 10^{-27} m ought to realise that it cannot make sense for the effective separation to be smaller than the diameter of the nucleus of an atom.

(d) (i) Most candidates that obtained an answer in **(c)(ii)** were able to use their separation with Newton's law of gravitation to determine the gravitational force between adjacent molecules. Some weaker candidates used the equation for gravitational field strength rather than gravitational force and omitted to square the mass in the numerator.

(ii) The hint in the question was that candidates needed to determine an order of magnitude for the weight of a molecule. Those that determined the 10^{-26} N figure and then drew a consistent conclusion about the validity of the assumption based on comparing 10^{-26} N with their answer in **(d)(i)** were awarded credit.

4(a)(i)	temperature = –273.15 °C	**A1**

4(a)(ii)	temperature = 0 K	**A1**

4(b)(i)	gas is ideal	**B1**

4(b)(ii)	$pV = NkT$	**C1**
	$N = 270 / (8.0 \times 10^{-21})$ $= 3.4 \times 10^{22}$	**A1**

4(b)(iii)	$n = (3.4 \times 10^{22}) / (6.02 \times 10^{23})$ $= 0.056$ mol	**A1**

4(c)	$\frac{1}{2} m\langle c^2 \rangle = (3 / 2) kT$	**C1**
	$\frac{1}{2} \times m \times 1900^2 = 1.5 \times 8.0 \times 10^{-21}$ ($m = 6.65 \times 10^{-27}$ kg)	**C1**
	$m = (6.65 \times 10^{-27}) / (1.66 \times 10^{-27})$	**C1**
	$= 4.0$ u	**A1**

Question 4

(a) Weaker candidates confused the temperature scales in **(i)** and **(ii)**, reversing their answers. Some candidates incorrectly rounded their answer in **(i)** to a whole number.

(b) (i) Candidates were generally able to identify the gas as being an ideal gas. Weaker answers simply gave an expression in symbols without indicating anything about the nature of the gas.

(ii) This question was well answered.

(iii) This question was well answered, with candidates generally using the correct expression, then showing their working in full before expressing their answer to the correct number of significant figures.

(c) Stronger candidates laid out their working clearly, appreciating that an answer in kilograms required conversion to atomic mass units. The final answer was not exactly 4 u, so two significant figures were required. Weaker candidates often did not recognise that an r.m.s. speed was given, which needed to be squared to obtain the mean-square speed. Some candidates were incorrect in the way they expressed the mean-square speed in symbol form, creating an incorrect meaning to their expression.

3(a)	(gas that obeys) $pV \propto T$ (at all values of p, V and T)	**M1**
	where T is thermodynamic temperature	**A1**

3(b)(i)	$pV = \frac{1}{3} Nm\langle c^2 \rangle$ **and** $Nm / V = \rho$ $(p = \frac{1}{3} \rho \langle c^2 \rangle)$	**C1**
	r.m.s. speed = $\sqrt{\langle c^2 \rangle}$	**C1**
	$1.6 \times 10^5 = \frac{1}{3} \times 1.9 \times \langle c^2 \rangle$ leading to r.m.s. speed = 500 m s^{-1} **or** r.m.s. speed = $\sqrt{(3 \times 1.6 \times 10^5 / 1.9)}$ = 500 m s^{-1}	**A1**

3(b)(ii)	$(pV =) \frac{1}{3} Nm\langle c^2 \rangle = NkT$ (so) $\frac{1}{2} m\langle c^2 \rangle = (3 / 2) kT$	**C1**
	$\frac{1}{2} \times 4.7 \times 10^{-26} \times 503^2 = (3 / 2) \times 1.38 \times 10^{-23} \times T$ T = 290 K	**A1**
	or	
	$pV = NkT$ **and** $Nm / V = \rho$ (so) $T = pm / \rho k$	**(C1)**
	$T = 1.6 \times 10^5 \times 4.7 \times 10^{-26} / (1.9 \times 1.38 \times 10^{-23})$ = 290 K	**(A1)**

3(c)	potential energy (of molecules) is zero	**B1**
	$U = N \times ½\, m\langle c^2 \rangle = 6.0 \times 6.02 \times 10^{23} \times ½ \times 4.7 \times 10^{-26} \times 503^2$ **or** $U = N \times (3 / 2)\, kT = 6.0 \times 6.02 \times 10^{23} \times (3 / 2) \times 1.38 \times 10^{-23} \times 287$ **or** $U = n \times (3 / 2)\, RT = 6.0 \times (3 / 2) \times 8.31 \times 287$	**C1**
	$U = 21000$ J	**A1**

Question 3

(a) This question was generally well answered. Many weaker candidates did not identify the temperature used in the relationship as being thermodynamic temperature.

(b) (i) Stronger candidates ensured that the correct symbol $\langle c^2 \rangle$ was used throughout their answer. Weaker candidates did not use $\langle c^2 \rangle$ for root-mean-square speed or used it incorrectly. Many candidates showed confusion over mass and density, believing the density was the mass of one molecule divided by the volume of the gas.

(ii) The use of the ideal gas equation $pV = NkT$ to form an equation involving molecular kinetic energy illustrated a better understanding in general than the relationships tested in **(i)**. More candidates achieved full credit here than in **(i)**.

(c) The calculation of the internal energy was the part of this question that was most successfully answered, and there were also many candidates who a gave good explanation of the reason for ignoring molecular potential energy in their calculations. Weaker candidates often confused the number of moles with the number of molecules.

4(a)(i)	thermodynamic temperature	**B1**

4(a)(ii)	molar gas constant	**B1**

4(b)(i)	m: mass of one molecule (of the gas)	**B1**
	$\langle c^2 \rangle$: mean-square speed (of molecules)	**B1**

4(b)(ii)	$NBT / A = \frac{1}{3} Nm\langle c^2 \rangle$	**M1**
	clear use of $E_K = \frac{1}{2} m\langle c^2 \rangle$ leading to $E_K = 3BT / 2A$	**A1**

4(c)	line with positive gradient passing through the origin	**B1**
	smooth curve with decreasing positive gradient	**B1**

Question 4

(a) (i) Most candidates were able to identify the meaning of T as thermodynamic or absolute temperature.

(ii) Many candidates were able to correctly deduce the meaning of B as the molar gas constant in this question. Common misconceptions were that B represented either the Boltzmann constant or magnetic flux density.

(b) (i) Some candidates were confused in this part over whether they were dealing with a single molecule or all the molecules. The symbol m had to be identified as the mass of a single molecule, and $\langle c^2 \rangle$ as the mean-square speed of all the molecules.

(ii) This question was generally well answered, although some candidates converted the question in their minds into the derivation of $E_K = (3/2)kT$ without substituting back for the expression in terms of A and B.

(c) Most responses seen warranted at least partial credit. Straight lines or curves curving the wrong way were usually the reasons for not achieving full credit.

3(a)(i)	(P and Q are at the) same temperature	**B1**
	no <u>net</u> transfer of thermal energy (between P and Q)	**B1**

3(a)(ii)	$Q = mc\Delta T$	**C1**
	$24 \times 10^3 = (0.54 \times 390 \times \Delta T) + (0.37 \times 910 \times \Delta T)$	**C1**
	$\Delta T = 44\,\text{K}$	**A1**

3(b)(i)	work done $= p\Delta V$	**C1**
	$= (1.6 \times 10^5) \times (0.18 - 0.32)$	**C1**
	$= -2.2 \times 10^4\,\text{J}$	**A1**

3(b)(ii)	$pV = NkT$	**C1**
	$N = (1.6 \times 10^5 \times 0.18) / (1.38 \times 10^{-23} \times 273)$ $= 7.6 \times 10^{24}$	**A1**

3(b)(iii)	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$	**C1**
	r.m.s. speed $= \sqrt{[(3 \times 1.38 \times 10^{-23} \times (210 + 273) / (4.7 \times 10^{-26})]}$ $= 650\,\text{ms}^{-1}$	**A1**

Question 3

(a) (i) Generally well answered by the stronger candidates. However, several misconceptions are worth highlighting. Firstly, many candidates appeared to think that ‘constant temperature’ and ‘equal temperatures’ mean the same thing. Secondly, many candidates confused internal energy and thermal energy and gave answers that were contradictory.

(ii) Most candidates knew the general equation for specific heat capacity and were therefore able to achieve the first ‘working’ mark. However, only the strongest candidates correctly analysed the energy transfers involved to arrive at the correct answer.

(b) (i) Many candidates correctly used the equation for work done on a gas when changing volume at constant temperature. However, only the strongest candidates realised that, because the gas is expanding, the work done on the gas must be negative.

(ii) Generally well-answered. However, one misconception that was common in a minority of candidates, warrants mention. Having correctly stated the starting equation $pV = NkT$, some candidates substituted the change in volume from part **(b)(i)** as the value of V.

(iii) Generally well-answered by the stronger candidates. The common confusion among weaker candidates was the difference between r.m.s. speed and mean-square speed. Many candidates stopped at the mean-square speed and gave this as their answer to the r.m.s. speed.

4(a)	• molecules are in (constant) random motion • (all) collisions between molecules are (perfectly) elastic • no forces between molecules (except during collisions) • volume of molecules is negligible (compared with volume of gas) • collisions involving molecules are instantaneous *Any three points, 1 mark each*	**B3**

4(b)	• molecules collide with (walls of) container • momentum of molecule changes during collision (with walls) • change in momentum is caused by force on molecule by wall • molecule experiences force from wall so molecule exerts force on wall • many molecules exerting force across the area of the wall leads to pressure (on the wall) *Any three points, 1 mark each*	**B3**

4(c)	*Any three bulleted points from:* • both gases are ideal *Up to 2 points from:* • mass of one molecule of gas X is 3.3×10^{-27} kg • mass of one molecule of gas Y is 6.6×10^{-27} kg • mass of one molecule of gas Y is double mass of one molecule of gas X *Up to 2 points from:* • sample of X contains 0.27 mol / 1.6×10^{23} molecules • sample of Y contains 0.81 mol / 4.9×10^{23} molecules • sample of Y contains treble the amount of gas / number of molecules as sample of X *Up to 2 points from:* • mass of gas X is 5.4×10^{-4} kg • mass of gas Y is 3.2×10^{-3} kg • mass of gas Y is six times mass of gas X	**B3**

Question 4

(a) Candidates who knew their 'bookwork' were generally able to correctly state three of the assumptions of the kinetic theory. Weaker candidates often gave responses in terms of 'gases' rather than the molecules that make up the gas. A common misconception was that the assumption dealing with the negligible volume of the molecules related to a single molecule rather than to all of the molecules in the gas.

(b) Many candidates answered a different question from the one asked, and discussed why pressure increases with temperature. Of the candidates that did address the question asked, most observed that there are molecular collisions with the walls of the container, but only the strongest candidates discussed the application of Newton's laws to those collisions to explain the origin of the force on the walls.

(c) Many candidates offered descriptions of the graphs rather than drew conclusions about the gases and their samples. Responses that treated quantities that vary as if they were properties of the samples were common. There were many different points that candidates could make by way of conclusions about the gases and their samples, and stronger candidates frequently achieved full credit.

3(a)(i)	number of particles per unit amount of substance	**B1**

3(a)(ii)	$N_A = R / k$	**B1**

3(b)(i)	X pressure and Y pressure <u>both</u> = NkT / V	**B1**
	X amount = N / N_A **and** Y amount = $2N / N_A$	**B1**
	X mean-square speed = $3kT / m$ **and** Y mean-square speed = $3kT / 2m$	**B1**
	X internal energy = $3NkT / 2$ **and** Y internal energy = $3NkT$	**B1**

3(b)(ii)	line passing through the origin and not returning to either axis	**B1**
	curve with positive decreasing gradient	**B1**

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2(a)	(if in thermal contact) no net transfer of (thermal) energy (between them)	**B1**

2(b)(i)	$pV = nRT$	**C1**
	$T = (1.20 \times 10^5 \times 0.0260) / (0.740 \times 8.31)$ $(= 507\ \text{K})$	**M1**
	temperature = 507 – 273 = 234 °C	**A1**

2(b)(ii)	thermal equilibrium so temperatures (of X and Y) are equal	**B1**
	$pV = NkT$	**C1**
	$N = (2.90 \times 10^5 \times 0.0430) / (1.38 \times 10^{-23} \times 507)$ $= 1.78 \times 10^{24}$	**A1**

2(b)(iii)	• (molecular) kinetic energy is proportional to temperature **or** kinetic energy (of molecules) is same in both cylinders • kinetic energy proportional to mass × mean-square speed **or** temperature proportional to mass × mean-square speed **or** r.m.s. speed proportional to √(temperature / mass) • mean-square speed inversely proportional to mass **or** r.m.s. speed inversely proportional to √(mass) *Any two bulleted points, 1 mark each*	**B2**
	r.m.s. speed (of molecules) in X is half r.m.s. speed (of molecules) in Y	**B1**

Question 2

(a) There was a widespread misunderstanding that thermal equilibrium results in no transfer of thermal energy at all between the two objects. Candidates who realised that the rate of transfer of energy between them is constant, and so there is no net transfer between them, were awarded credit.

(b) (i) Very many candidates achieved full credit in this question. As always with a 'show that' question, marks are not awarded for getting to the answer, but for showing the working that leads to the answer. The common reasons for credit not being awarded were not showing the full substitution into $pV = nRT$ or not showing the final subtraction of 273 to convert the temperature from kelvin to degrees Celsius.

(ii) Most candidates were awarded credit for the correct starting equation, but some did not realise that the precision of the data provided in the question demanded a three significant figure answer. Others neglected the 'explain your reasoning' aspect of the question, and did not explain that the temperatures of the two gases are equal as a consequence of their being in thermal equilibrium.

(iii) Many candidates achieved at least partial credit, and many of the strongest candidates were awarded full credit. Among weaker candidates there was considerable confusion between r.m.s. speed and mean-square speed.

3(a)(i)	gas for which $pV \propto T$	**M1**
	where T is thermodynamic temperature	**A1**

3(a)(ii)	no intermolecular forces	**B1**
	(so) potential energy is zero	**B1**

3(b)(i)	$pV = NkT$	**C1**
	$N = (2.0 \times 10^5 \times 0.26) / (1.38 \times 10^{-23} \times 290)$ $= 1.3 \times 10^{25}$	**A1**

3(b)(ii)	$E_K = (3/2)\ kT$	**C1**
	$E_K = (3/2) \times 1.38 \times 10^{-23} \times 290$ $= 6.0 \times 10^{-21}$ J	**A1**

3(b)(iii)	internal energy = total KE + PE of molecules **or** PE = 0 so internal energy = total KE of molecules	**B1**
	internal energy $= 1.3 \times 10^{25} \times 6.0 \times 10^{-21}$ $= 7.8 \times 10^4$ J	**A1**

3(c)	straight line with positive gradient	**B1**
	line passing through the origin	**B1**

Question 3

(a) (i) The majority of candidates were able to achieve full credit. Where this was not possible, the ideal gas relationship between *p, V* and *T* was usually given correctly in one form or another, but the symbol *T* was not identified as the thermodynamic temperature. Occasionally an inappropriate physical constraint such as standard conditions was included.

(ii) The majority of the candidates identified both the assumption of no intermolecular forces and the implication of zero potential energy. The inclusion of a second basic assumption of the kinetic theory sometimes negated a correct answer regarding the intermolecular forces.

(b) (i) Many candidates gained full credit for this calculation.

(ii) When it was appreciated that only one molecule was being considered, many candidates achieved full credit. Some candidates gave an answer to only one significant figure. Weaker candidates often did not identify the correct starting equation $E = (3/2)kT$.

(iii) Whilst many candidates were able to combine their answers to the previous two questions (allowing for errors carried forward) to give an accepted numerical answer, the explanation of their reasoning was often incomplete. In particular, although many candidates understood that the potential energy of the molecules was zero, they rarely explained that the internal energy was the sum of the individual molecular kinetic energies. The symbols E_K and KE were often used without indicating whether they referred to one or all molecules.

(c) The majority of the candidates identified the proportionality between the volume of the gas and its internal energy, and drew a straight line with a positive gradient. Stronger candidates showed the line clearly going through the origin. Weaker candidates sometimes described a negative or inverse relationship between the two variables.

2(a)	total kinetic energy associated with random motion of molecules	**M1**
	plus total potential energy (of molecules) but potential energy is zero	**A1**

2(b)(i)	$W = p\Delta V$	**C1**
	$= 1.01 \times 10^5 \times 5.20 \times 10^{-5}$ $= (+)5.25$ J	**A1**

2(b)(ii)	$V \propto T$ *or* V / T = constant	**C1**
	$1.24 / (273 + 20) = (1.24 + 0.520) / T$ $T = 416$ K	**A1**

2(b)(iii)	$c = Q / m\Delta T$	**C1**
	$= 960 / (0.016 \times (416 - 293))$ $= 490$ J kg^{-1} K^{-1}	**A1**

2(c)	no change in volume so no work is done (by the gas)	**B1**
	(same temperature change so) same change in internal energy	**B1**
	less thermal energy needs to be supplied so c is less	**B1**

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2(a)(i)	work done per unit mass	**B1**
	work (done) moving mass from infinity (to the point)	**B1**

2(a)(ii)	$\phi = -GM / r$ $= -(6.67 \times 10^{-11} \times 7.3 \times 10^{22}) / (1.7 \times 10^{6})$	**C1**
	$= -2.9 \times 10^{6}\ \text{J kg}^{-1}$	**A1**

2(b)(i)	$E_P = m\phi$	**B1**

2(b)(ii)	$\frac{1}{2}mv^2 + m\phi = 0$	**M1**
	correct algebra leading to $v = \sqrt{(-2\phi)}$	**A1**

2(c)	speed $= \sqrt{(2 \times 2.9 \times 10^{6})}$ $= 2400\ \text{m s}^{-1}$	**A1**

2(d)	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$	**C1**
	$3.34 \times 10^{-27} \times \langle c^2\rangle = 3 \times 1.38 \times 10^{-23} \times 400$	**C1**
	$c_{\text{r.m.s.}} = 2200\ \text{m s}^{-1}$	**A1**

2(e)	r.m.s. speed is an average so many molecules have speeds greater than the escape speed **or** there is a distribution of molecular speeds (around the r.m.s. value) so many molecules have speeds greater than the escape speed	**B1**

Question 2

(a) (i) Most candidates were awarded at least partial credit, but full credit was often not possible because of a dimensionally incorrect definition that gave an energy rather than an energy per unit mass.

(ii) Most candidates were able to be awarded credit for the substitution of the given numbers into the equation for gravitational potential. Some candidates did not realise that gravitational potential must be negative or did not know the unit.

(b) (i) Most candidates realised that the magnitude of potential energy is obtained by multiplying the potential by the mass, but a significant minority thought that there is a negative relationship between gravitational potential and gravitational potential energy. Some weaker candidates attempted to give expressions in terms of quantities other than the two asked for in the question.

(ii) This was generally well answered by candidates who realised that the loss in kinetic energy of the particle must equal the gain in gravitational potential energy, though some were a little confused over signs in the starting equation. Many weaker candidates tried to answer this question by equating gravitational and centripetal forces.

(c) This question was generally well answered, with most candidates able to use their answer to **(a)(ii)** with the given equation to calculate a speed.

(d) Many of the more able candidates calculated the correct answer with relative ease, although a significant minority forgot to take the square root of their value of mean-square speed at the end. Some of the weaker candidates realised that the starting point required the mean kinetic energy to be equated with $(3/2)kT$, but then found the subsequent arithmetic difficult. Many others were a little confused and attempted to equate $(3/2)kT$ with $(1/3)Nm\langle c^2\rangle$.

(e) This was another challenging question. Even many of the stronger candidates missed the point that, even though the r.m.s. speed of the molecules is a little less than the escape speed, there is a *distribution* of molecular speeds in which the r.m.s. value is only an average. As a result, many of the molecules do have the speed required to escape, and over time all will do so. Many responses did not discuss molecular speeds at all, and only referred to the speed of the gas or of the Moon.

3(a)(i)	N: number of molecules (of the gas)	**B1**
	m: mass of one molecule (of the gas)	**B1**
	$\langle c^2 \rangle$: mean square speed (of molecules)	**B1**

3(a)(ii)	$pV = NkT$	**M1**
	$NkT = \frac{1}{3}Nm\langle c^2 \rangle$ **and** $E_K = \frac{1}{2}m\langle c^2 \rangle$ leading to $E_K = (3/2)\,kT$	**A1**

3(b)	$\frac{1}{2} \times 3.34 \times 10^{-27} \times 9300^2 = (3/2) \times 1.38 \times 10^{-23} \times T$	**C1**
	$T = 6980$ K	**A1**

3(c)(i)	$L = F \times 4\pi d^2$	**C1**
	$L = 2.52 \times 10^{-8} \times 4\pi \times (4.16 \times 10^{16})^2$ $= 5.48 \times 10^{26}$ W	**A1**

3(c)(ii)	$L = 4\pi\sigma r^2 T^4$ $5.48 \times 10^{26} = 4\pi \times 5.67 \times 10^{-8} \times r^2 \times 6980^4$	**C1**
	$r = 5.69 \times 10^8$ m	**A1**

3(d)	(very high pressure so) molecules are (very) close together (*not just 'nearer'*)	**B1**
	forces between molecules are not negligible **or** volume of molecules not negligible compared with gas volume	**B1**

NOT FOUND:
9702_w23_qp_41 EXAMINER REPORT (Qu 3)

2(a)(i)	(gas that obeys) $pV \propto T$ (for all values of p,V and T)	**M1**
	where T is thermodynamic temperature	**A1**

2(a)(ii)	temperature = –273.15 °C	**A1**

2(b)(i)	$pV = NkT$	**C1**
	$N = (1.37 \times 10^5 \times 0.640) / (1.38 \times 10^{-23} \times (227 + 273))$	**C1**
	$= 1.27 \times 10^{25}$	**A1**

2(b)(ii)	mass $= 0.0424 / (1.27 \times 10^{25})$ $= 3.34 \times 10^{-27}$ kg	**A1**

2(b)(iii)	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$	**C1**
	$3.34 \times 10^{-27} \times v^2 = 3 \times 1.38 \times 10^{-23} \times 500$	**C1**
	$v = 2490$ m s^{-1}	**A1**
	or	
	$pV = \frac{1}{3}(Nm)\langle c^2\rangle$ and Nm = mass of gas	**(C1)**
	$0.0424 \times v^2 = 3 \times 1.37 \times 10^5 \times 0.640$	**(C1)**
	$v = 2490$ m s^{-1}	**(A1)**

2(c)	sketch: line from (0, 0) to (500, v)	**B1**
	line with decreasing positive gradient throughout	**B1**

Question 2

(a) (i) Most candidates were able to state that an ideal gas is one that obeys the relationship $pV \propto T$ for all values of p, V and T. Fewer went on to clarify that T is the thermodynamic temperature. Some weaker candidates did give the correct relationship, but then contradicted it by stating that it only applies under certain conditions (such as when T is constant or under standard conditions). A significant minority of candidates confused the definition of an ideal gas with the basic assumptions of the kinetic theory.

(ii) The syllabus requires candidates to know the exact value of the conversion between temperatures in kelvin and temperatures in degrees Celsius, and so credit was awarded to candidates who gave the value of absolute zero as –273.15 °C.

(b) (i) The more able candidates had little difficulty with this question, and were generally awarded full credit for a correct answer after identifying the correct starting equation and performing the calculation to the three significant figure precision warranted by the data in the question. Many of the weaker candidates used the wrong starting equation and calculated a number of moles, and appeared to think that this was what the question required. Calculation of a number of moles, with no attempt at a conversion to obtain the number of molecules, could not be awarded credit.

(ii) Most candidates realised that the answer to this question required the division of the mass of the gas by their answer to **(b)(i)**. It was possible to obtain credit here from an incorrect answer to **(b)(i)** through the standard error carried forward principle. Some candidates did not appreciate that the data still demands a three significant figure answer.

This is a question where candidates should pause to think about the plausibility of their answer. It was not uncommon to see incorrect answers giving the mass of a molecule of the order of 10^{26} kg. Candidates who carried out a quick check of the sense of their answer would have realised that a mistake must have been made in such a calculation.

(iii) There were two possible methods to answer this question, one of which used the mass of a molecule and the other of which used the mass of the gas. Confusion between the two was very common, and only the more able candidates were able to arrive at the correct final answer.

(c) Most candidates were able to be awarded at least partial credit, for a line between (0, 0) and (500, v). Some lines went well beyond the 500 K maximum temperature and could not be awarded credit. Credit for deducing the correct direction of curvature was generally only obtained by the stronger candidates.

4(a)	• particles are in (continuous) random motion • particles have negligible volume (compared with the gas) • negligible forces between particles (except during collisions) • (all) collisions (perfectly) elastic • time of collision negligible (in comparison with time between collisions) *Any two points, 1 mark each*	**B2**

4(b)(i)	(general starting equation) $pV = nRT$	**C1**
	$T = (2pV / nR)$ where R is the (molar) gas constant	**A1**

4(b)(ii)	sketch: straight vertical line XY from $(V, 2p)$ to (V, p)	**B1**
	straight horizontal line YZ from (V, p) to $(2V, p)$	**B1**
	curve with gradient increasing from Z to X from $(2V, p)$ to $(V, 2p)$	**B1**

<table>
<tr><td rowspan="5">4(b)(iii)</td><td>XY work done on gas correct (= 0)</td><td>B1</td></tr>
<tr><td>ZX increase in internal energy correct (= 0)</td><td>B1</td></tr>
<tr><td>YZ work done on gas correct (= $-pV$)</td><td>B1</td></tr>
<tr><td>XY increase in internal energy such that the increase in internal energy column adds up to zero</td><td>B1</td></tr>
<tr><td>all three thermal energies transferred such that $\Delta U = q + w$ in each row

(completely correct answer:

<table><tr><th>change</th><th>ΔU</th><th>Q</th><th>w</th></tr><tr><td>X to Y
Y to Z
Z to X</td><td>$-U$
[$+U$]
0</td><td>$-U$
$U + pV$
$-W$</td><td>0
$-pV$
[$+W$]</td></tr></table>
)</td><td>B1</td></tr>
</table>

Question 4

(a) The basic assumptions of the kinetic theory of gases are generally well known. Candidates sometimes referred to the volume of the gas rather than the volume of the particles. Others incorrectly referred to the volume of a single particle.

(b) (i) Most candidates started with the correct equation here. Some candidates then did not go on to use the conditions given in the question which included a pressure of $2p$ when the volume was V. Some candidates did not rearrange the starting equation to make T the subject when they had been asked to determine an expression for T.

(ii) There were many correct responses here, although the line drawn to join Z to X was often a straight line rather than a curve. Some candidates drew more than two dots and some did not add the lines. The lines were needed to show the variation of the pressure with the volume as required by the question.

(iii) Only the strongest candidates correctly completed this table in full. Many candidates found it difficult to correctly apply the first law of thermodynamics for the three changes. They often did not know where to begin on the table, which was by filling in the information for changes already given to them. The information for the remaining changes was deduced from these. Finally, some candidates used letters that were not appropriate, for example a Q to denote thermal energy and a single letter p, which was not an energy.

2(a)	gas for which $pV \propto T$	**M1**
	where T is thermodynamic temperature	**A1**

2(b)(i)	evidence of two temperature conversions between °C and K	**B1**
	two calculations shown, one for each state e.g. $\frac{1.10\times10^{5}\times540\times10^{-6}}{(273+27)} = 0.198$ **and** $\frac{6.70\times10^{6}\times30\times10^{-6}}{(273+742)} = 0.198$	**A1**

2(b)(ii)	work is done on the gas	**M1**
	internal energy increases (so temperature increases)	**A1**

2(b)(iii)	$pV = NkT$ e.g. $N = \frac{1.10\times10^{5}\times540\times10^{-6}}{1.38\times10^{-23}\times300}$ $= 1.435\times10^{22}$ $\Delta E_k = (3/2)\, k\Delta TN$	**C1**
	$= (3/2)\times1.38\times10^{23}\times(742-27)\times\frac{1.10\times10^{5}\times540\times10^{-6}}{1.38\times10^{-23}\times300}$	**C1**
	$= 212\,\text{J}$	**A1**

2(c)	$E = mc\Delta\theta$ **and** $E = mL$	**C1**
	$\Delta\theta$ = (27 + 196) or 223	**C1**
	E = 0.0240 × 1.04 × (27 + 196) + 0.0240 × 199 = 10.3 kJ	**A1**

Question 2

(a) There was much confusion here between the definition of an ideal gas and the assumptions of the kinetic theory. The stronger candidates defined the symbols, including 'thermodynamic temperature' for *T*.

(b) (i) Most candidates were able to use the provided data to show that the helium gas was behaving as an ideal gas. A few candidates omitted the conversion from temperature in degrees Celsius to kelvin.

(ii) Many candidates gave answers that confused internal and thermal energy, and whether the gas is doing work or having work done on it. Many candidates regarded the internal energy and the change in internal energy as the same thing. For example, comments such as 'ΔU increases' were common, where the correct comment would have been either 'U increases' or 'ΔU is positive'.

(iii) Most candidates calculated the change in kinetic energy for a single molecule, rather than the change in the total kinetic energy of the molecules of the gas. A few who completed the correct calculation did not write the final answer to the expected 3 significant figures because the data was given to 3 significant figures. A few candidates incorrectly added 273 to the temperature change.

(c) Most candidates were able to set up this calculation. However, many candidates then made an error with significant figures or subtracting the two energies calculated, rather than adding them. Candidates were confused by the final negative temperature and the removal of thermal energy.

3(a)	p = pressure (of gas), V = volume (of gas) **and** k = Boltzmann constant	**B1**
	N = number of molecules	**B1**
	T = thermodynamic temperature	**B1**

3(b)	($pV = NkT$ and $pV = \frac{1}{3}Nm\langle c^2\rangle$ leading to) $NkT = \frac{1}{3}Nm\langle c^2\rangle$	**M1**
	algebra leading to $(3/2)kT = \frac{1}{2}m\langle c^2\rangle$ **and** use of $\frac{1}{2}m\langle c^2\rangle = E_K$ leading to $(3/2)kT = E_K$	**A1**

3(c)(i)	T = 296 K	**C1**
	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$ $\frac{1}{2} \times 5.31 \times 10^{-26} \times u^2 = (3/2) \times 1.38 \times 10^{-23} \times 296$	**C1**
	u = 480 m s^{-1}	**A1**

3(c)(ii)	line passing through (P, u)	**B1**
	horizontal straight line	**B1**

Question 3

(a) The meanings of the terms in the equation were generally well known. Common errors were confusion between number of molecules and amount of substance for N, and not being clear that T is thermodynamic temperature.

(b) This syllabus derivation was generally well articulated by most candidates.

(c) (i) Candidates who realised they had to equate $\frac{1}{2}mu^2$ with the $(3/2)kT$ expression given in the previous part were generally able to substitute the relevant numbers and then calculate the answer. Some candidates did not realise that the quantity that comes out of this calculation is the r.m.s. speed, and thought they had to also divide by $\sqrt{2}$. Some of the weaker candidates were unable to make a start because they did not realise that the temperature needed to be converted from °C to K.

(ii) This was a higher-level question intended to discriminate between the more able candidates. Candidates were expected to realise that the r.m.s. speed of the molecules depends only on the temperature of the gas, and that the gas remaining in thermal equilibrium with its surroundings meant that the temperature is constant. A variety of interesting curves and lines were seen, but the strongest candidates were able to deduce that the correct line is a horizontal straight line at r.m.s. speed u.